Flight Testing of Wireless Sensing Networks for Rotorcraft Structural Health and Usage Management Systems

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Abstract

The goal of this work was to demonstrate, in an operational environment, a network of hard-wired and wireless sensors for next generation rotorcraft structural health and usage management systems (SHUMS). Wireless sensors on the rotating components included energy harvesting to eliminate battery maintenance. The SHUMS system included a wireless sensor data aggregator (WSDA), an energy harvesting wireless pitch link node, a wireless structural vibration sensor node, wireless structural strain sensor nodes, and a hard wired attitude heading reference sensor (AHRS). With the Global Positioning Systems (GPS) as a timing reference, the WSDA used periodic wireless beaconing to maintain precise time synchronization among the all nodes. The system was installed on a Sikorsky MH-60S. Synchronized wireless and wired sensor data, collected at various sample rates, were successfully aggregated using time as a unifying variable. This system can monitor a wide variety of machines and structures, including wind turbines, heavy equipment, rotating machinery, and helicopters.

Keywords: Wireless, Sensing, Synchronized Networks, Energy Harvesting, Rotorcraft, SHM, HUMS, SHUMS

Introduction

Energy harvesting, combined with wireless communications, has the potential to enable sensors to become very deeply embedded for long term aircraft structural loads tracking. The US Navy seeks advanced, next generation sensing systems that can track the precursors to crack formation and initiation [1]. The ideal monitoring system would directly record component loading histories to provide a rich data base of information to accurately measure structural fatigue and to enable component lives to be safely extended.

We have previously reported on the first flight test of an energy harvesting wireless component (the pitch link) aboard a Bell M412 helicopter [2]. We have since developed a synchronized system for wireless sensor data aggregation and remote reporting [3]. Network scalability and collision avoidance was achieved by time division multiple access (TDMA) [4]. However, in order for these capabilities to mature to mission readiness, they must be refined through system flight testing.

Objectives

The goal of this work was to demonstrate, in an operational environment, a network of hard-wired and wireless sensors for next generation rotorcraft structural health and usage management systems (SHUMS). Wireless sensors on the rotating components included energy harvesting capability to eliminate battery maintenance.

In addition to providing a demonstration during flight, our objective was to demonstrate to the Navy a highly flexible and versatile wireless data acquisition system, capable of self-configuration. There are a wide variety of sensors currently available, and new sensing technologies will continue to emerge in the future. These capabilities should be able to be added (or subtracted) as required for a given platform and monitoring application. The requisite sample rates from all the sensors in the wireless network should be easily configured to match the specific needs of the customer.

To this end, we set out to provide a system of wireless nodes that could be easily configured to support a wide range of data collection needs. This included over-the air programming to enable identical sample rates with simultaneous data conversion from distinct wireless sensor nodes, such as may be required to monitor arrays of structural strain sensors or load sensing nodes on pitch links, lead-lag dampers, and discrete strain gauges. The system must also support data collection from nodes that may be programmed to sample at much lower rates, such as may be required to monitor temperatures, humidity levels, or corrosion in key locations within the aircraft. Burst mode sampling at very high rates should also be supported in order to facilitate data collection from vibration sensors that may be used on the gearboxes or rotor hub.

The user setup should be very fast and easy, so that once the network sample rates have been entered, network communications should be automatically scheduled by the system, and this scheduling should be transparent to the end user.

Methods

The platform chosen for these tests was a Sikorsky MH-60S operated by the US Navy/NAVAIR in Patuxent River, MD.

The SHUMS system included a wireless sensor data aggregator (WSDA-MIL), powered by the aircraft's 28VDC power, energy harvesting wireless pitch link node, structural vibration sensing node (G-Link-MIL), battery powered wireless structural strain sensor nodes (SG-Link-MIL, and a hard wired attitude heading reference sensor (AHRS, 3DM-GX3-35). The AHRS was powered by the WSDA's integral USB interface. The strain sensors and accelerometer were mounted on the external wing stricture. The WSDA's Ethernet port provided an open architecture, bi-directional digital communications interface for programming and data download. All the hardware and software used during these tests was designed and built by MicroStrain, Inc. (Williston, VT, USA).

The WSDA used the Global Positioning Systems (GPS) as a time reference combined with periodic wireless beaconing to maintain precise (31 microsecond) time synchronization among the nodes. Pitch link data were acquired during the flight test at 64 Hz sample rates. Data were aggregated within the WSDA using time as a unifying variable. Wireless nodes used the IEEE802.15.4 spread spectrum radio standard in the 2.4 GHz band. Each node included a precision timekeeper chip, stable to +/- 3 parts per million over a temperature range of -40 to +85 degrees C.

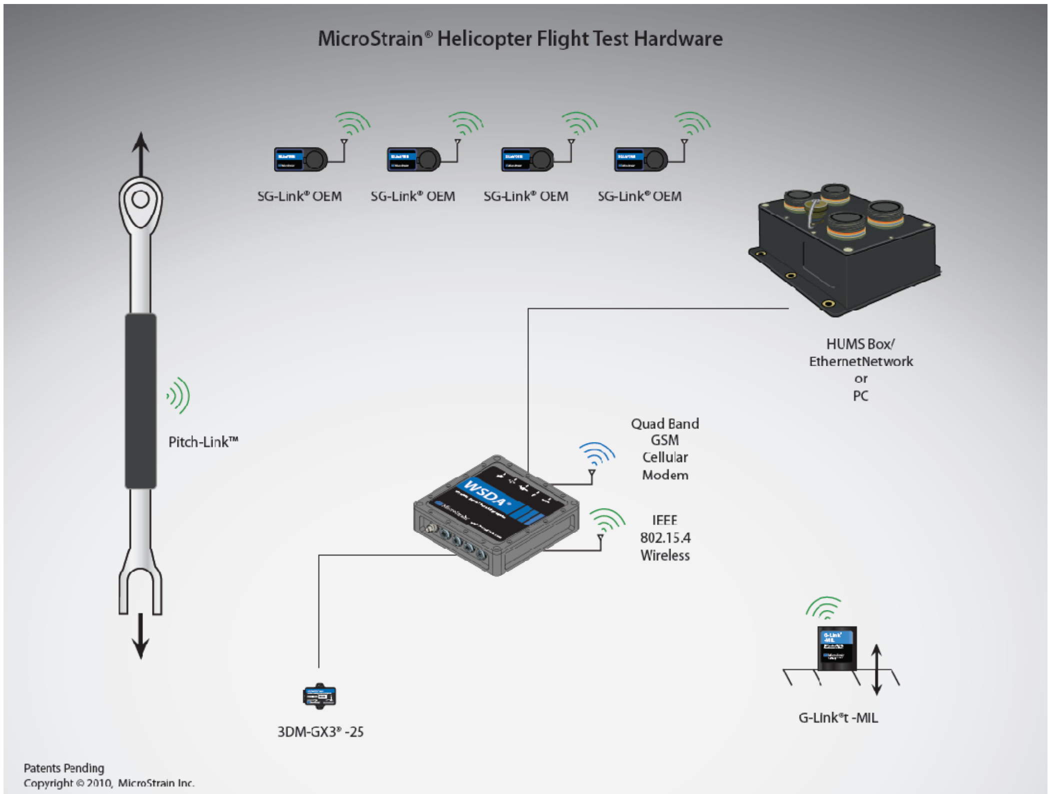
Prior to flight, wired and wireless sensor nodes were tested for radiated and conducted emissions and susceptibility to MIL-STD-461F electromagnetic interference (EMI) standards and flight qualified. A wireless site survey was also conducted on a Navy MH-60S Sierra at Paxtuxent River NAS, Maryland. Wireless 802.15.4 signal strength was evaluated within the aircraft, and found to be sufficient at each sensor location. Reception of the GPS signal was tested indoors, within the aircraft's hanger, and found to be reliable. Table I summarizes all the elements of the system and their programmed sample rates. The entire system was installed in one working day. Figure 1 provides an illustration of the various wired and wireless subsystems which were supported.

We note that the WSDA includes an open architecture Ethernet interface, which was intended for direct wired connection to a Health and Usage Monitoring System (HUMS) box, however, this was not used during the tests described herein. The WSDA can also support GSM cellular telephone or satellite connectivity, but these capabilities were not enabled. For these flight tests, data were automatically aggregated within the WSDA, but the aggregated data download required a direct connection to the WSDA's Ethernet port.

Table I: Wired and Wireless System Configuration for MH-60S Flight Test

Description	**Quantity**	**Sensing channels**	**Units**	**Sample Rate**
WSDA-MIL	1	Radio signal strength for all wireless nodes	RSSI	-
3DM-GX3-35 AHRS	1	roll, pitch, yaw, roll rate, pitch rate, yaw rate, GPS time	Radians, Radians per second, UTC time in seconds	100 Hz continuous
Pitch-Link	1	Strain gauge	Lbf	64 Hz for 1 sec every 5 secs
SG-Link-MIL	4	Uni-axial Strain gauge	Microstrain	64 Hz continuous
G-Link-MIL	1	Triaxial accelerometer, temperature	G's degF	64 Hz continuous

Figure 1: Diagram of System Configuration for MH-60S Flight Test

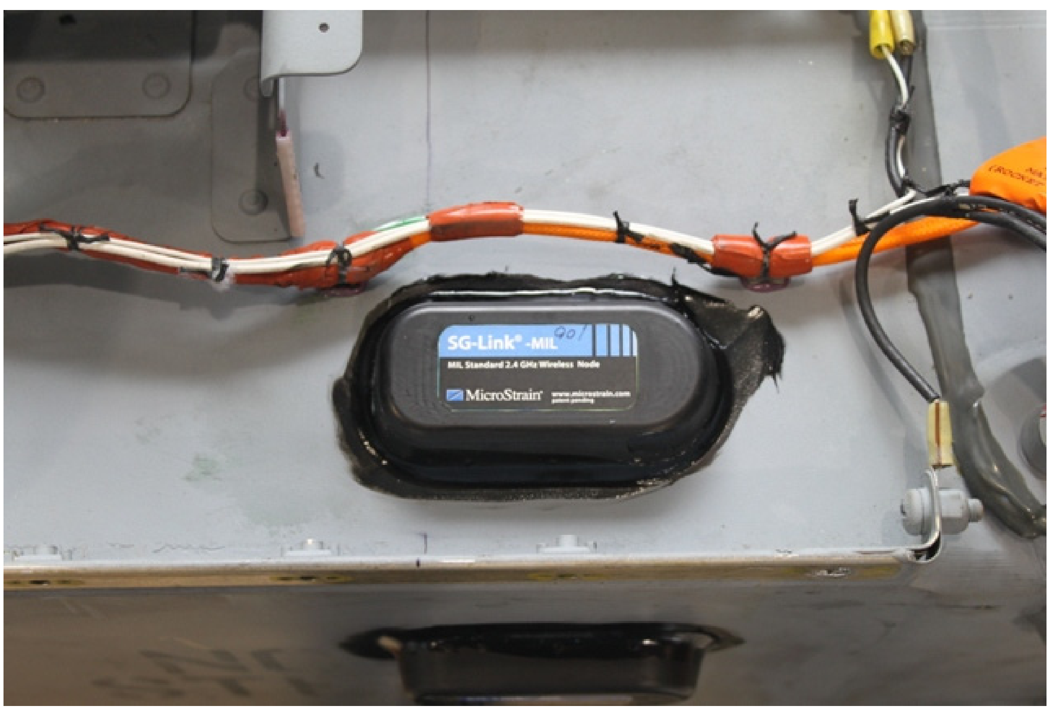


Figures 2-4 (below) provide photographs of the various elements of the wireless SHUMS system as installed on the MH-60S.

Figure 2: Wireless Sensor Data Aggregator (WSDA-MIL) installed aboard MH-60S

Figure 3: Wireless Pitch-Link node installed aboard MH-60S

Figure 4: Wireless strain sensor node (SG-Link-MIL) installed aboard MH-60S



Results

User Configuration Protocols and Beaconed Network Capacity

An improved beacon protocol which allows for simultaneous operation of devices with varied sampling requirements and bandwidths was used to facilitate the flight test setup and network configuration. The improved protocols enable a wide range of network and node configurations to be supported. A setup routine enables users to view and manage the beacon scheduling configuration in a straight forward manner. The user first selects the nodes that they wish to configure for a beacon session. The nodes are then listed in descending order of their bandwidth requirements, based on their current sample rate settings and number of active channels. The user then clicks on “Apply Network Configuration” and the software attempts to calculate a network scheduling solution that satisfies the communication requirements for each node. If it is unable to do so, it notifies the user that there is insufficient bandwidth for the given set of nodes and node configurations. The user then has the option to either remove nodes from the group or reduce the sample rate of one or more nodes.

Table II below provides the maximum node capacity for a network of Microstrain's synchronized wireless sensor nodes using the 802.15.4 radio transceiver (Texax Instruments CC2420), where all nodes in the network are continuously sampling one sensor channel at a uniform sampling rate. The node capacity is shown to increase linearly with decreasing sample frequency. Two exceptions exist, the first being that the total capacity is capped at 1638, even for nodes sampling in the sub hertz region. This guarantees that all sampled data will arrive to the base station within 16 seconds of measurement. The other exception is that the 512 Hz sampling rate requires smaller transmit packets, and thus more frequent transmissions.

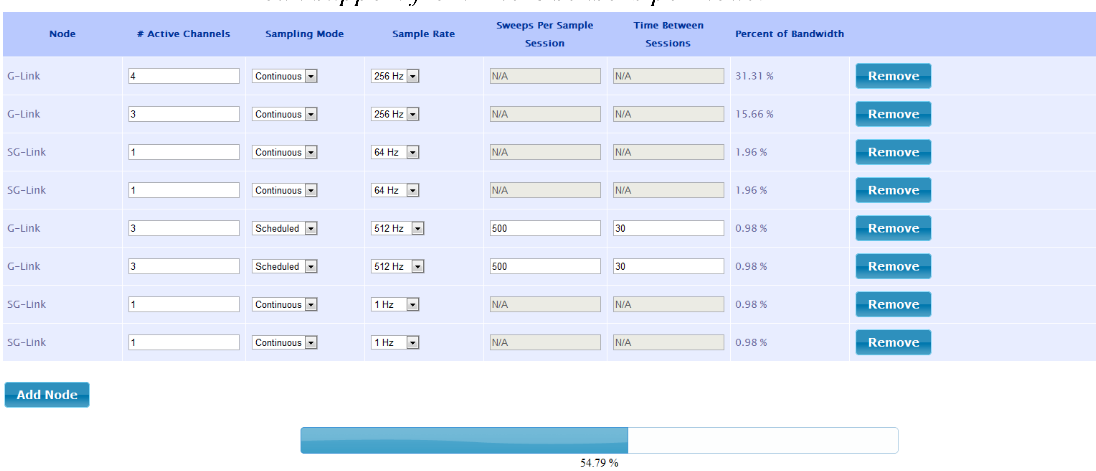
Table II: Wireless System Node Capacity and Aggregate Sample Rate w/ 802.15.4

Sample Rate (Hz)	Maximum Node Capacity	Aggregate Sample Rate
< 1 Hz	1638	
1	1638	1638
2	1638	3276
4	819	3276
8	409	3272
16	204	3264
32	102	3264
64	51	3264
128	25	3200
256	12	3072
512	3	1536

Sample Rates of 32 Hz to 4096 Hz, as well as 100 kHz on the HS-Link, are supported by using scheduled burst sessions. In this mode, the node performs the sampling session at a periodic interval and uses the time in between sessions to transmit its data. In applications where high rates are necessary or where continuous, real-time data is not required, this mode can drastically increase the capacity of the network.

The network also supports combinations of varying sampling rates, sensor channels, and sampling modes. The screenshot of the Synchronized Sampling Configuration Wizard (Figure 5, below) illustrates one such network. In this example network, 4 G-Links (acceleration sensor) and 4 SG-Links (strain sensor) display the percent of bandwidth they require for their given configuration. These eight wireless nodes, supporting 17 total sensors, are only using 54.8 % of the total network bandwidth allowed per radio frequency.

Figure 5: Screenshot of the Synchronized Sampling Configuration Wizard. In this example, a qty of four wireless strain sensor nodes and four wireless accelerometer nodes are set up for samples rates of 512 Hz, 256Hz, 64 Hz, and 1 Hz. Various nodes can support from 1 to 4 sensors per node.



Node	# Active Channels	Sampling Mode	Sample Rate	Sweeps Per Sample Session	Time Between Sessions	Percent of Bandwidth	
G-Link	4	Continuous	256 Hz	N/A	N/A	31.31 %	Remove
G-Link	3	Continuous	256 Hz	N/A	N/A	15.66 %	Remove
SG-Link	1	Continuous	64 Hz	N/A	N/A	1.96 %	Remove
SG-Link	1	Continuous	64 Hz	N/A	N/A	1.96 %	Remove
G-Link	3	Scheduled	512 Hz	500	30	0.98 %	Remove
G-Link	3	Scheduled	512 Hz	500	30	0.98 %	Remove
SG-Link	1	Continuous	1 Hz	N/A	N/A	0.98 %	Remove
SG-Link	1	Continuous	1 Hz	N/A	N/A	0.98 %	Remove

Pitch Link Energy Harvester Output and Power Consumption and Calibration

Two flight ready wireless energy harvesting pitch link nodes were tested for energy output at various load input levels and calibrated against a load cell using an hydraulic test machine (Instron) prior to shipment to the Navy. Power output from the piezoelectric strain energy harvesting material bonded to the pitch link for various strain levels are provided in Table III. The energy output from the strain harvester varied with load impedance and the applied dynamic load at 4.3 Hz, and ranged from 200 microwatts to 1.3 milliwatts. Load impedance can vary during use depending on the state of charge of the energy storage elements (super capacitors and thin film batteries), so we provide a range of impedances to reflect this variability.

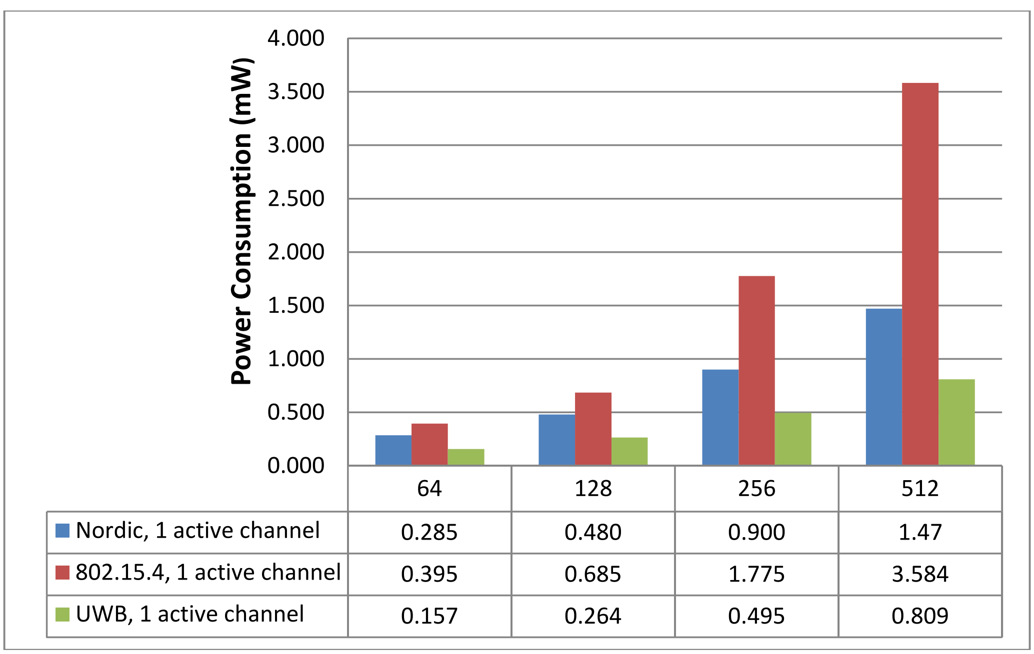
The power consumption of the pitch link nodes varies with the sample rate. As shown in Figure 6, the energy consumed varies from ~0.4 to 3.6 milliwatts. We have previously reported that duty cycling is more accurate than reducing sample rates for fatigue measurement applications when energy consumption must be reduced [5]. Therefore, in order to sustain sample rates of 64 Hz, we chose to implement duty cycling for the pitch link nodes to conserve energy during these flight tests.

We want to emphasize that the use of lower power radios, such as ultra wide band (UWB) radio transceivers (IEEE 802.15.4a) from Decawave (Dublin, Ireland) would allow higher sample rates to be attained for the same amount of available power. We previously reported on a 3 channel mast monitoring system that used the Nordic radio to achieve sample rates of 256 Hz on a Bell M407 platform [3]. The MicroStrain mast monitoring system continuously measured and transmitted mast torque and bending on orthogonal axes using the energy from bending strains (+/- 400 microstrain) generated by mast flap. This was independently verified by researchers at Bell Helicopter during whirl tower demonstrations [6]. Note however, that the Nordic radios used were not spread spectrum radios, and therefore do not provide process gain. The limited RF communications range (less than 10 meters line of sight) of Nordic transceivers precluded their use in the Navy's MH-60S flight test demonstrations reported here.

Table III: Output power as measured from pitch link strain harvester #201 tested at various cyclic load levels (+1250 lb preload,4.3 Hz)

Impedance	+-500Lbs	+-750Lbs	+-1000Lbs
25K	0.2mW	0.44mW	0.8mW
50K	0.28mW	0.7mW	1.3mW
100K	0.3mW	0.7mW	1.3mW

Figure 6: Power consumption for single channel wireless nodes (such as the pitch link) with various radio transceivers (Nordic, 802.15.4, and UWB) as a function of 4K ohm strain gauge sample rates of 64, 128, 256, and 512 samples/second.



Pitch Link Calibration

Load calibration data obtained for one of the instrumented pitch links is provided in Figure 7. Dynamic tests were also performed prior to shipment at load increments of 1250 lbs (static compression), +/- 500 lbs, +/- 1000 lbs, +/- 500 lbs, and 0 (remove static compression) as a final check. Typical dynamic load test data are provided in Figure 8. The reference load cell output is plotted in pound force on the vertical axis as a function of digital output (in bits) on the horizontal axis.

Figure 7: Load calibration test data for energy harvesting wireless pitch link #201.

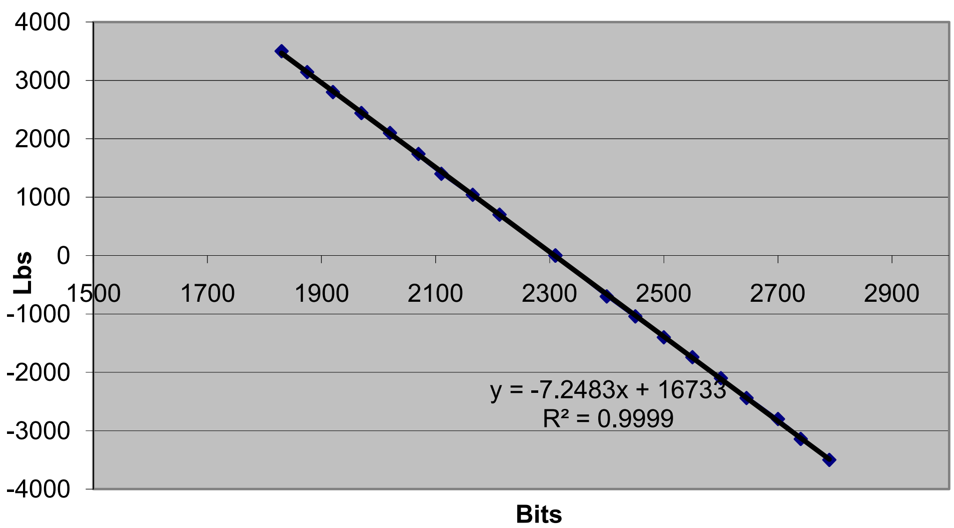
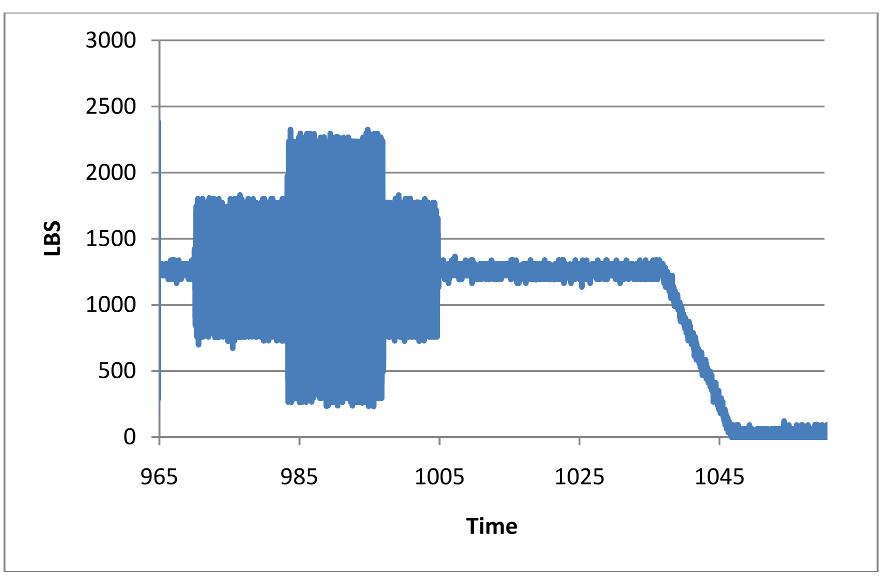


Figure 8: Dynamic test data for energy harvesting wireless pitch link #201. The reference load cell output is plotted in pounds force on the vertical axis as a function of digital output (in bits) on the horizontal axis.



Flight Test Data

At the time of this writing (8 October, 2010), our Navy flight testing program is ongoing. In this section, we provide a summary of flight test data based on the Navy MH-60S flights during August of 2010. All data from wired and wireless nodes were recorded in the WSDA. The WSDA was programmed to automatically respond to the application of 28VDC power by waking the wireless nodes from sleep mode and initializing them for data collection. All flight test data from the wireless network and the wired AHRS inertial sensors were aggregated in the WSDA into a SQL database using time as a unifying variable and referenced to the Universal Time Clock (UTC).

Figure 9 provides a record of the 3-axis (triaxial) angular rate data as recorded by the WSDA from the 3DM-GX3-35 AHRS from August 16th and 17th, 2010. There was significant inertial activity of ~ 1 hour duration recorded on August 16th from UTC 19:12 to 20:20, and once again on August 17th from UTC 13:55 to 15:00. There are also periods of low inertial inactivity that are recorded prior to and after each flight test event. These sections represent data collected when the vehicle is on the ground and 28VDC power is activated. Figure 10 provides a close-up view of the inertial (angular rate) data from August 16th, 2010 during UTC 19:12 to 20:20.

Figure 9: Triaxial angular rate data recorded on August 16th and 17th, 2010

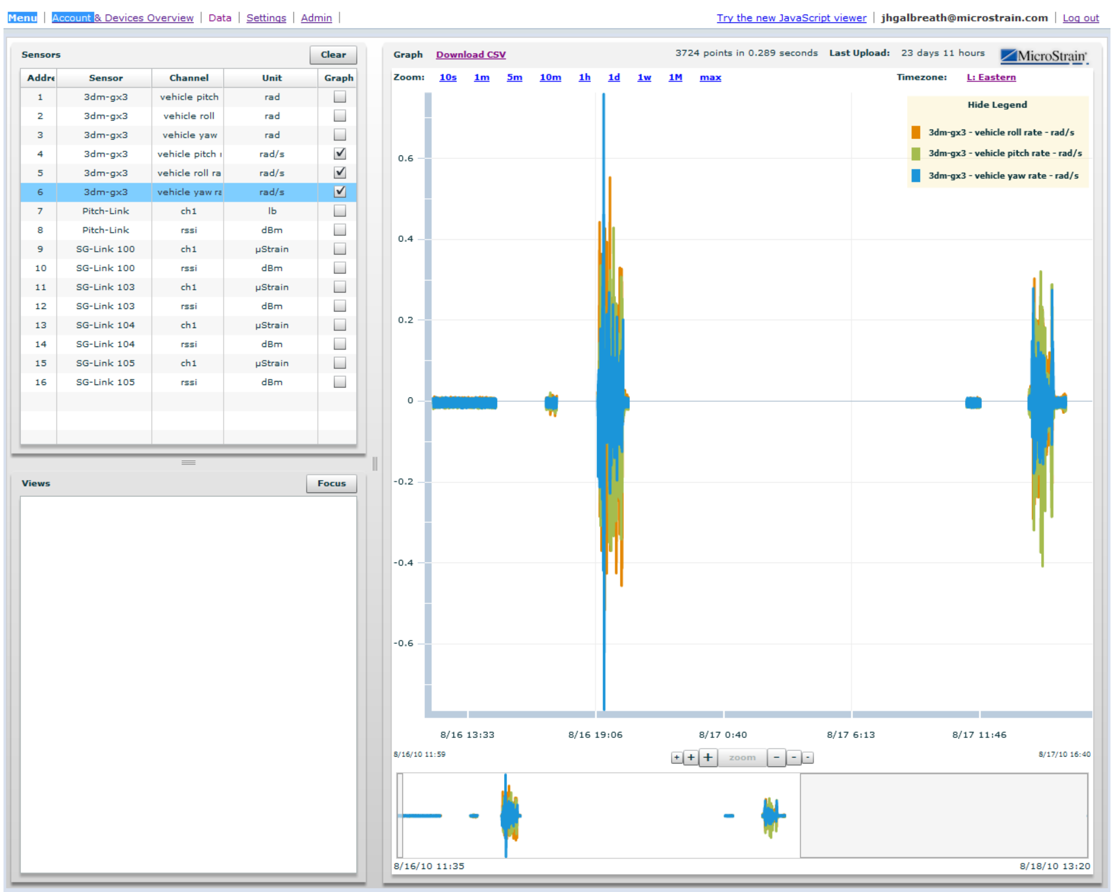
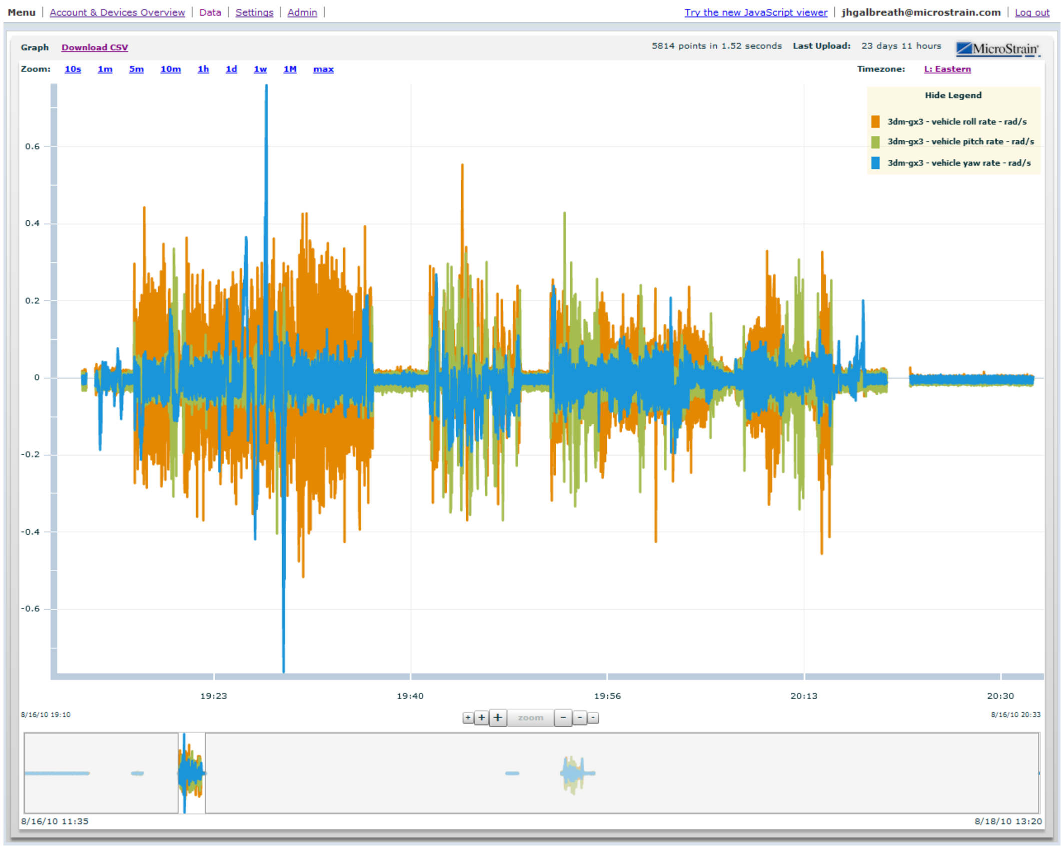


Figure 10: Triaxial angular rate data of August 16th, 2010 from UTC 19:12 to 20:20



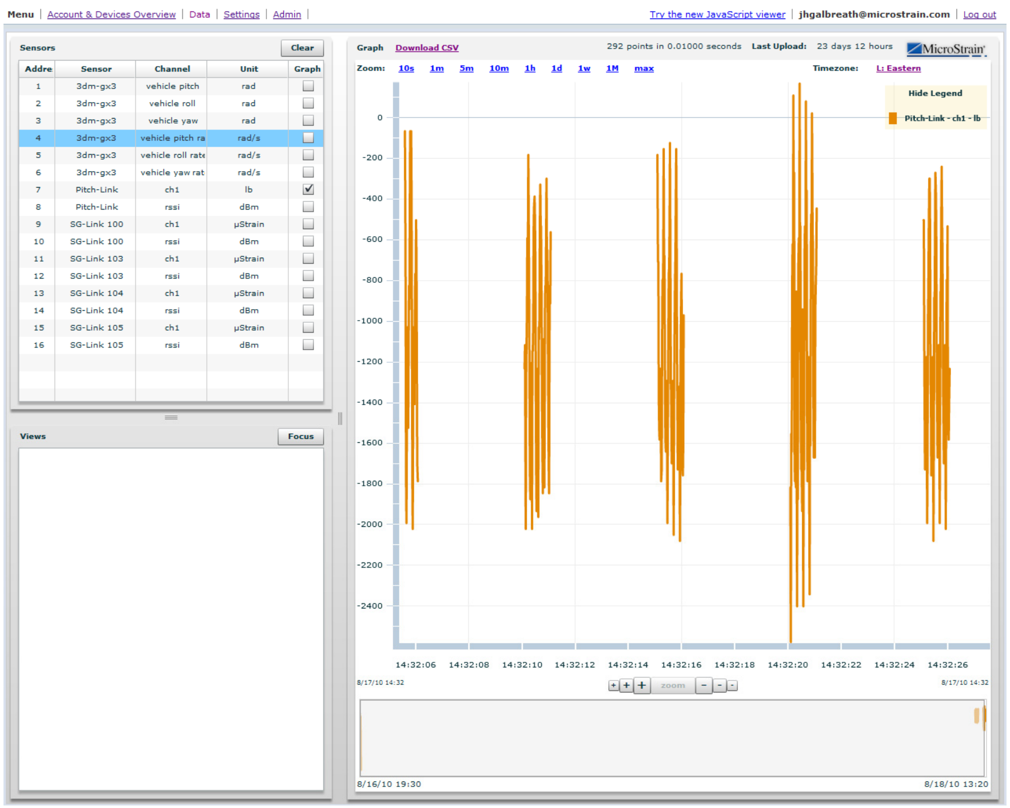
Data from three of the four SG-Link-MIL nodes (installed on opposite faces of the box wing) are presented in Figure 11. Data from the fourth strain sensor was not plotted in this graph, but that sensor was operating reliably and its data were eliminated from Figure 11 for clarity.

Strain events of the largest magnitude can be observed on August 16 at 19:41 UTC. SG-Link-MIL nodes #100 and #105 both recorded a similar strain event with magnitude of 40 microstrain. Timing of this event appears to correlate with a change in vehicle attitude, as measured by the roll and pitch channels of the 3DM-GX3-35 AHRS inertial sensor and plotted as a function of time in Figure 11.

Figure 11. Flight test data - Wireless Strain (top) vs. Vehicle Yaw sensors (bottom).

The wireless pitch-link node recorded loads information on August 16th and August 17th. A section of recorded wireless pitch-link loads data from the August 17th flight is shown in Figure 12. Note that the pitch-link was configured for burst mode data collection at a sample rate of 64 Hz, sampling 1 second of data every 5 seconds.

Figure 12: MH-60S Pitch-Link flight test data from August 17th, 2010. This wireless pitch link was set up for burst mode sampling at 64Hz for 1 second every 5 seconds. Note that the fourth burst shows higher activity and loading in compression.



Conclusions

This work reports on the first flight tests of a synchronized wireless structural monitoring system aboard a helicopter. The system is software programmable; capable of collecting data from a wide variety of sensor types, including strain gauges, load cells, torque sensors, thermocouples, accelerometers, magnetometers, and angular rate sensors. The gains, offsets, number of active channels and sample rates may all be wirelessly configured.

The configuration wizard enables users to quickly and easily configure the system for their applications. The setup supports time synchronized wireless sampling from multiple nodes as well as a range of wireless sensor sample rates and burst mode duty cycles. Once installed, the system operates autonomously to aggregate time stamped data. When equipped with cellular and/or satellite uplinks, it will automatically push these data to a secure server.

This system can be used to monitor fixed and rotary wing aircraft, bridges, buildings, heavy equipment, wind turbines, and other critical structures. Combined with energy harvesters, these new wireless sensing networks can be deeply embedded into structures and structural components for improved condition based maintenance (CBM) and advanced structural health and usage management systems (SHUMS).

Acknowledgements

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